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Low-activation concrete design of the Danish Center for Particle Therapy

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Motivation

- Neutrons induce **significant radioactivity** in the concrete walls close to the energy degrader
- If activity concentration > EU exemption level at the end-of-life of DCPT

→ **Significant cost** for wall demolition, transport, and long-term storage of radioactive concrete

Background

Radiation safety design of proton centers:

Design tasks	Traditional	DCPT
Shielding barrier thickness		
MC modeling of concrete activation		
Development of a dedicated low-activation concrete		
Full low-activation bunker design for walls, floor, and ceiling		

Trento: MC simulation in forward direction + special sand with low Eu content

Uppsala: Marble concrete walls in the cyclotron and ESS bunker

Long-lived radionuclides in concrete

Most common neutron-induced long-lived radionuclides in concrete:

Radio-nuclide	**Dominant production mechanism**	**Half life (years)**	**EU exemption level (kBq/kg)**
Cs-134	$^{133}Cs(n,\gamma)$	2.06 y	0.1
Na-22	$^{23}Na(n,2n)$, $^{27}Al(n,\alpha+2n)$, $^{24}Mg(n,p+2n)$, $^{28}Si(n,n+2p+\alpha)$	2.60	0.1
Co-60	$^{59}Co(n,\gamma)$	5.27	0.1
H-3	$^{6}Li(n,\alpha)$, $^{7}Li(n,\alpha+n)$	12.3	100 (only beta decay)
Eu-152	$^{151}Eu(n,\gamma)$	13.5	0.1

Activity > Exemption level: Material is classified as radioactive waste

Calculation of concrete activation

Activity of radionuclides in concrete close to DCPT degrader after 30 years of operation of DCPT [1]:

$$a_{radio} = R_{p,1\ year} \frac{\rho_A}{\rho} \int_0^{250\ MeV} \Phi(E)\sigma(E)dE \cdot \left(1 - e^{-\lambda \cdot 30\ years}\right)$$

$R_{p,1\ year}$: Average rate of proton loss	ρ_A: Atomic density of target nuclides
$\Phi(E)$: Differential neutron fluence per proton	ρ: Density
$\sigma(E)$: Reaction cross section	λ: Decay constant of the radionuclide

Main input to the calculation:

- $R_{p,1\ year}$: Proton workload at the degrader
- ρ_A: Concrete composition
- $\Phi(E)$: MCNPX MC simulation of neutron fluence
- $\sigma(E)$: ENDF database , IAEA

1. Shielding Design and Radiation Safety of Charged Particle Therapy Facilities, PTCOG Report 1

Concrete composition of DCPT concrete

Element	Content (weight %)
C	7.6 %
O	51.1 %
Na	0.8 %
Mg	0.1 %
Al	2.4 %
Si	21.8 %
Ca	13.4 %
Fe	1.5 %
Li	8.6 ppm
Cs	0.46 ppm
Co	3.4 ppm
Eu	0.39 ppm

Production of Na-22

Production of H-3 and Cs-134

Production of Co-60 and Eu-152

DCPT concrete specification:

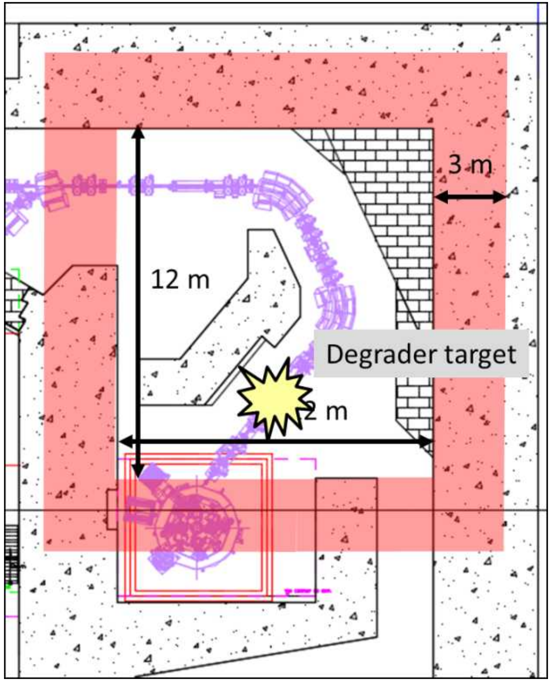
- Standard concrete with Danish sand and stone
- Density: 2.25 g/cm^3

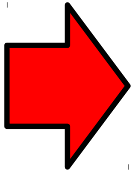
Steel reinforcement: 120 ppm cobalt

MC model of ESS bunker

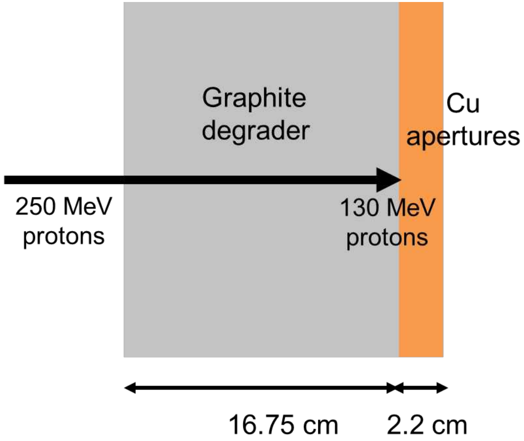
Most protons are lost at the degrader and the nearby Cu apertures

➡ Sufficient with **MC simulation of the ESS bunker**

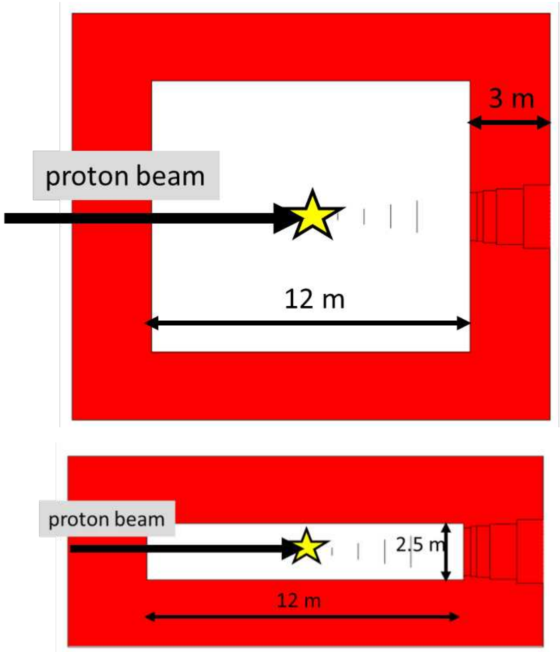




MC model of degrader target:



MC model of ESS bunker walls:



Activity concentration in ESS bunker walls after 30 years

Radionuclide			Eu-152	Co-60	Co-60	Na-22	Na-22	Na-22	Na-22	Na-22
Material			Concrete	Concrete	Steel rebar	Concrete	Concrete	Concrete	Concrete	Concrete
Target isotope			Eu-151	Co-59	Co-59	Na-23	Al-27	Mg-24	Si-28	Sum
Location	**Distance (m)**	**Depth (m)**	**Activity concentration (kBq/kg)**							
Forward	6	0	**0.30**	0.08	**2.66**	**0.21**	0.09	0.02	**0.77**	**1.09**
Forward	6	0.25	**0.29**	0.07	**2.59**	**0.15**	0.06	0.02	**0.52**	**0.75**
Floor/ceiling	1.25	0	**0.38**	**0.10**	**3.43**	**0.67**	0.09	0.02	**0.34**	**1.13**
Floor/ceiling	1.25	0.25	**0.70**	**0.17**	**6.16**	**0.20**	0.03	0.01	**0.13**	**0.37**
Side wall:	6	0	**0.23**	0.06	**2.03**	0.04	0.00	0.00	0.02	**0.06**
Exemption level (kBq/kg)			**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

Too high activity of Eu-152, Co-60, and Na-22 for a **large volume of concrete**

➡ **Low-activation concrete** needed close to the degrader

Low-activation marble concrete

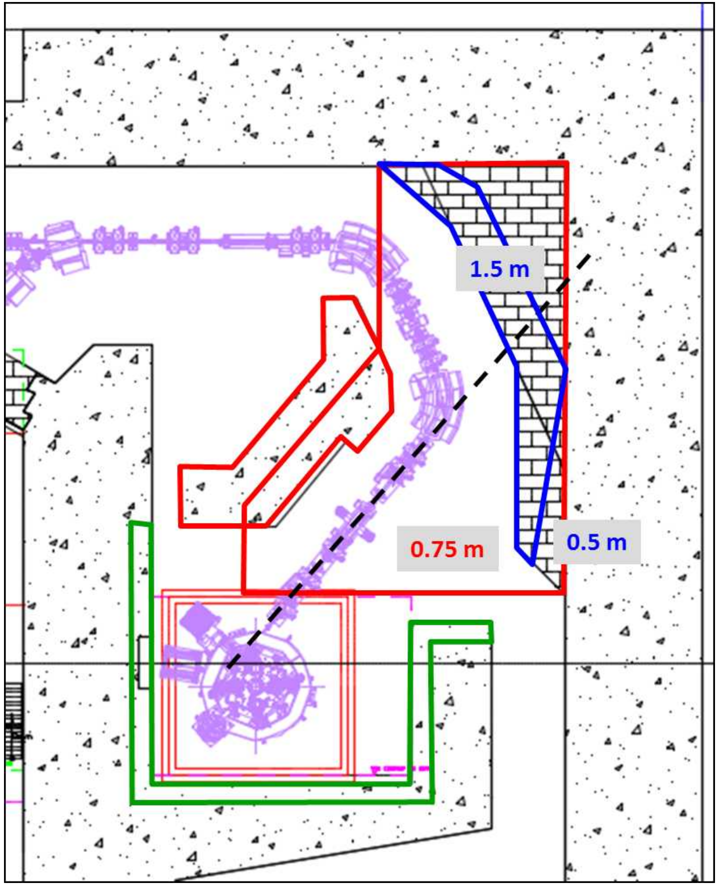
Marble concrete: DCPT concrete with sand/stone aggregates replaced by white Norwegian marble

Element	Content (weight %)	Max. allowed content (weight %) without violating exemption level
C	10.4 %	
O	37.4 %	
Na	<0.2 %	**0.12 %**
Mg	0.2 %	0.43 %
Al	0.6 %	2.6 %
Si	2.3 %	**2.8 %**
Ca	47.3 %	
Fe	0.9 %	
Li	3.7 ppm	128 ppm
Cs	<0.2 ppm	3.1 ppm
Co	1.8 ppm	**1.95 ppm**
Eu	<0.1 ppm	**0.06 ppm**

White Norwegian marble:

98.4 % calcite ($CaCO_3$)

Low-activation concrete design of the ESS bunker



Red area:

- Casting of marble concrete
- Reduce steel reinforcement to a minimum for the first 1 m

Blue area: Blocks of marble concrete

Green area: Avoid steel reinforcement for the first 0.5 m if possible

After 30 years of DCPT operation:

- Activity conc. in concrete < EU exemption level
- Activity conc. in steel rebar > EU exemption level (limited amount + can easily be separated)

Conclusion

We have...

- Developed a **general method** for calculation of concrete activation
- Calculated of max. **content of elements in ESS bunker** which do not violate exemption level
- Developed a **new low-activation concrete**
- Designed a **full low-activation bunker (walls, floor, and ceiling)**
  - Low-activity concrete
  - Reduced use of steel reinforcement